1993Ap&SS.205...69A

THE STARBURST MODEL FOR THE OPTICAL VARIABILITY OF THE SEYFERT 1 GALAXIES NGC 4151 AND NGC 5548

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(Received September, 1992)

Abstract. In the frame of the Starburst model, we show that the stellar processes expected to occur during the evolution of a metal rich massive stellar cluster can reproduce the observed optical light curves of the Seyfert 1 galaxies NGC 4151 and NGC 5548.

1. Introduction

In the Starburst model, the variability observed in radio quiet AGNs – i.e. Seyfert galaxies and most optically selected quasars – is thought to be produced by the supernova (SN) and compact supernova remnant (cSNR) activity resulting from the evolution of a metal-rich massive stellar cluster, product of a starburst in the nucleus of an early type galaxy (Terlevich *et al.*, 1987; 1992). The multifrequency spectrum of radio-quiet AGNs can be reproduced by the combined contribution of the young stars, SNe, cSNRs and dust present in a young stellar cluster with ages from 10 to 60 Myr (Terlevich, 1990). The basic Broad-Line Region parameters can be inferred from the evolution of these cSNRs in the high-density circumstellar medium (Terlevich *et al.*, 1992), and the observed delays of the responses of the lines to the variations of the continuum have proven to be well explained by thermal instabilities during shell formation (Tenorio-Tagle, 1992). Terlevich and Melnick (1985) also showed that this same stellar cluster, at previous evolutionary stages, can account for the emission line spectra of less active galactic nuclei, as Seyfert 2s and LINERs.

In this paper we address the question of whether this scenario is compatible with the best sampled optical light curves of Seyfert 1s: NGC 4151 and NGC 5548.

2. Light Curves of the Seyfert 1 Nuclei and Some Light Curves of Observed Supernovae

NGC 4151 and NGC 5548 have an extensive set of photometric observations reported by many authors during most of the 20th century. This database provides an excellent opportunity for a study of the history of the variations that take place

Astrophysics and Space Science **205:** 69–76, 1993.
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1993Ap&SS.205...69A

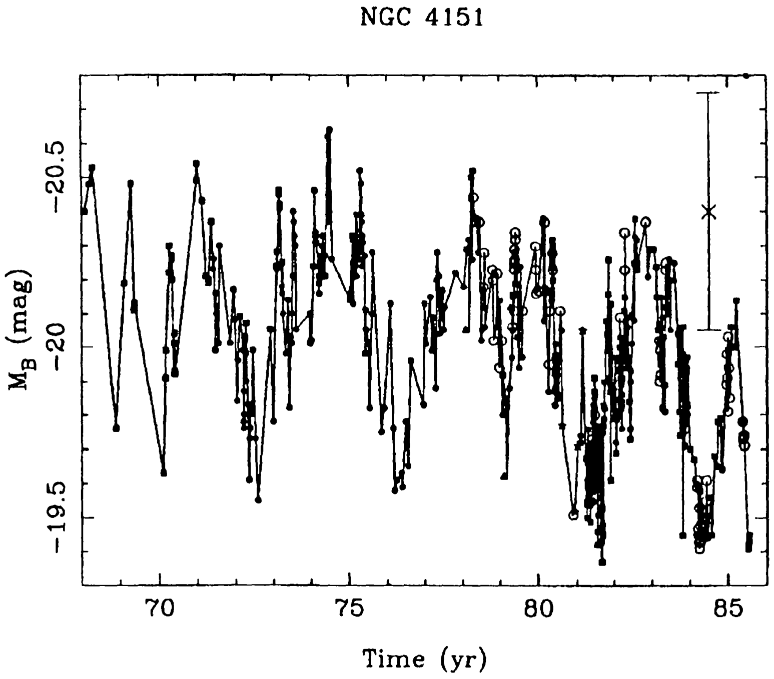

Fig. 1a. Light curve of NGC 4151. Data collected by M.V. Penston (private communication). The uncertainties in the derivation of the radial velocity of the galaxy are shown by the point with error bars at the right upper part of the panel.

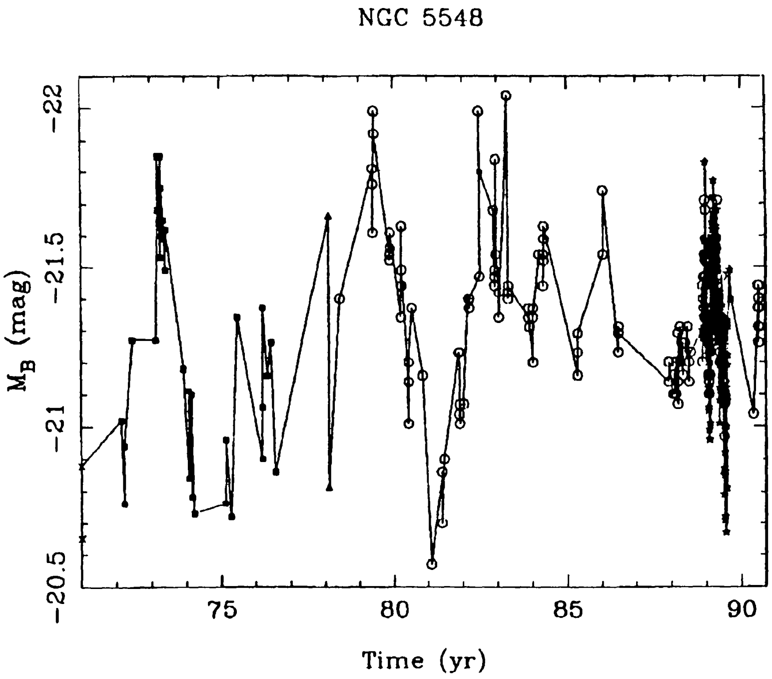

Fig. 1b. Light curve of NGC 5548. Data taken from Penston *et al.* (1974), Lyutyi (1977), Dibaĭ *et al.* (1984), Burstein *et al.* (1987), Lebofsky and Rieke (1980), Peterson *et al.* (1991) and IUE data base.

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1993Ap&SS.205...69A

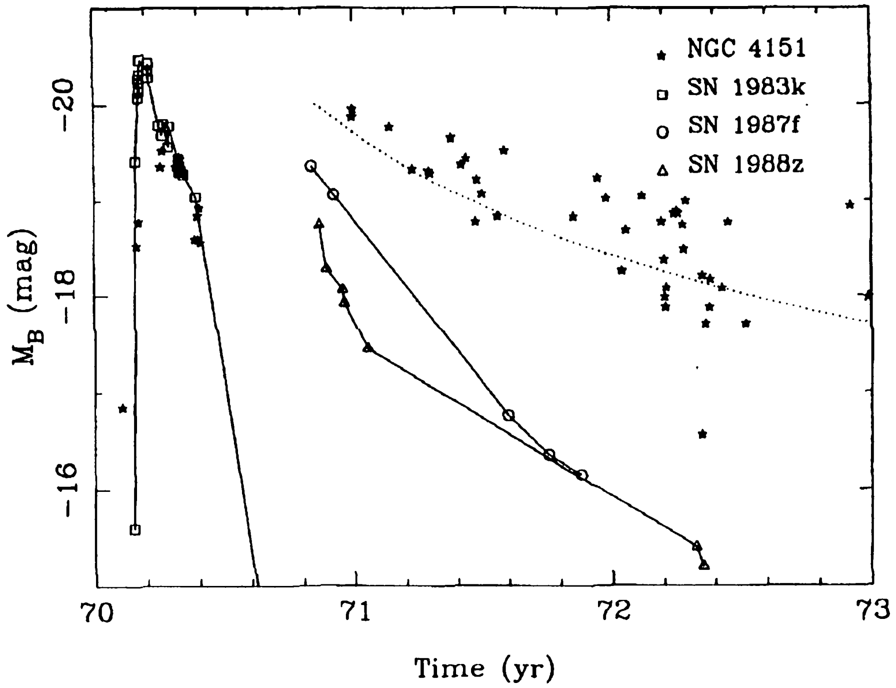

Fig. 2. Comparison of the net variation of the light curve of NGC 4151 to the light curves of SN 1983k, SN 1987f and SN 1988z.

in the nuclei of these galaxies. Figs. 1a and 1b ($H_0 = 50$ km s^{-1} Mpc^{-1} hereinafter) show the light curves of the nuclei of NGC 4151 and NGC 5548 after removing the light contamination from the underlying stellar bulges. Different symbols in the figures correspond to different photometries. The distance to NGC 4151 has been taken to be $v_r \simeq 1330$ km s^{-1}, different from its redshift $v = 978$ km s^{-1} (Sandage and Tammann, 1981) due to the peculiar velocity introduced by the infall towards the Virgo Cluster. The data have been corrected from extinction, $A_B = 0.66$ mag (Rieke and Lebofsky, 1981). The radial velocity and extinction assumed for NGC 5548 are $v_r \simeq 5220$ km s^{-1} (Sandage and Tammann, 1981) and $A_B = 0.42$ mag (Tsvetanov and Yancoulova, 1989; Walter and Courvoisier, 1990).

The first point to be checked is if the energy and amplitude of variation that SNe can produce is compatible with the observed variability amplitude. Fig. 2 shows the net variation of the nucleus of NGC 4151 around 1970–1973. We assume that the recorded minimum of light $M_B \simeq -19.5$ mag represents a non-variable component, presumably the young stellar cluster. The first peak in Fig. 2 is compared to a classical SN of type II, like SN 1983k (Phillips *et al.*, 1990), and the second one to SN 1987f (Filippenko, 1989) and SN 1988z (Stathakis and Sadler, 1991), peculiar type IIn SNe (Schlegel, 1990). SN 1983k was discovered in the Sab galaxy NGC 4699, $v \simeq 1511$ km s^{-1} (Barbon *et al.*, 1989), $v_r \simeq 2000$ km s^{-1}, with a measured extinction $A_B = 0.07$ mag produced in the Galaxy (Phillips *et al.*, 1990). SN 1987f was discovered in NGC 4615, $v_r \simeq 4746$ km s^{-1}, and SN 1988z

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1993Ap&SS.205...69A

in M+03 – 28 – 022 (Zw 095 – 049), $v_r \simeq 6660\,\mathrm{km\,s^{-1}}$ (Barbon *et al.*, 1989). The extinction produced in the parent galaxies of both SNe is unknown. SN 1983k accounts not only for the luminosity of the first peak in Fig. 2, but also for its amplitude, while SN 1987f and SN 1988z can account for the decay amplitude of the second peak. The luminosity of both SNe is somewhat lower than that of NGC 4151, but the intrinsic extinction produced in the parent galaxies could be very high, since they are embedded in H II regions (Filippenko, 1989; Stathakis and Sadler, 1991).

A double peak light curve is expected in the evolution of a SNR in a high density medium. The first peak would correspond to the SN explosion itself, and the second one to the time when the remnant reaches its radiative phase. This evolution is described by

$$L_B = \begin{cases} 6 \times 10^9 L_{B\odot} & \text{if } t = 0 \qquad \text{First peak} \\ 0 & \text{if } t = 110 \text{ days} \\ 0 & \text{if } t = 90 \text{ days} \\ 6 \times 10^9 L_{B\odot} \epsilon_{51}^{7/8}\, n_7^{3/4}\, (t/t_{sg})^{-11/7} & \text{if } t > t_{sg} \qquad \text{Second peak} \end{cases} \tag{1}$$

(*Note: Linear interpolation is used between 0 and 110 days for the first peak and 90 days and* t_{sg} *for the second one.*)
as derived from Terlevich *et al.*, (1992), where ϵ_{51} is the energy of the cSNR in 10^{51} erg units, n_7 the circumstellar density in $10^7\ \mathrm{cm^{-3}}$ units, and

$$t_{sg} = 0.62\mathrm{yr}\,\epsilon_{51}^{1/8}\, n_7^{-3/4}. \tag{2}$$

The dotted line in Fig. 2 reproduces the theoretical B band light curve of a cSNR for $\epsilon_{51} = 3$ and $n_7 = 1$, taking the time of the SN explosion in the first peak of the figure.

3. Numerical Simulations of the Light Curves of NGC 4151 and NGC 5548

We conclude that SNe can reproduce the energy and time scales of variation of well isolated peaks in the light curves of Seyferts. With this in mind, we can try to reproduce the overall pattern of variability observed in Fig. 1.

The B band luminosity arising from a young stellar cluster at its SN II phase, i.e., between 10 and 60 Myr, is due to the contribution of Main Sequence stars and SNe. The SN rate (ν_{SN}) and the blue luminosity coming from Main Sequence stars (L_B) are related. Fig. 3a shows the evolution of the ratio of these two quantities, as derived from the stellar models of Maeder and Meynet (1988) and Maeder (1990) for different Initial Mass Functions (IMFs). The relation ν_{SN}/L_B is almost independent of the assumed IMF and basically constant over the lifetime of this

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1993Ap&SS.205...69A

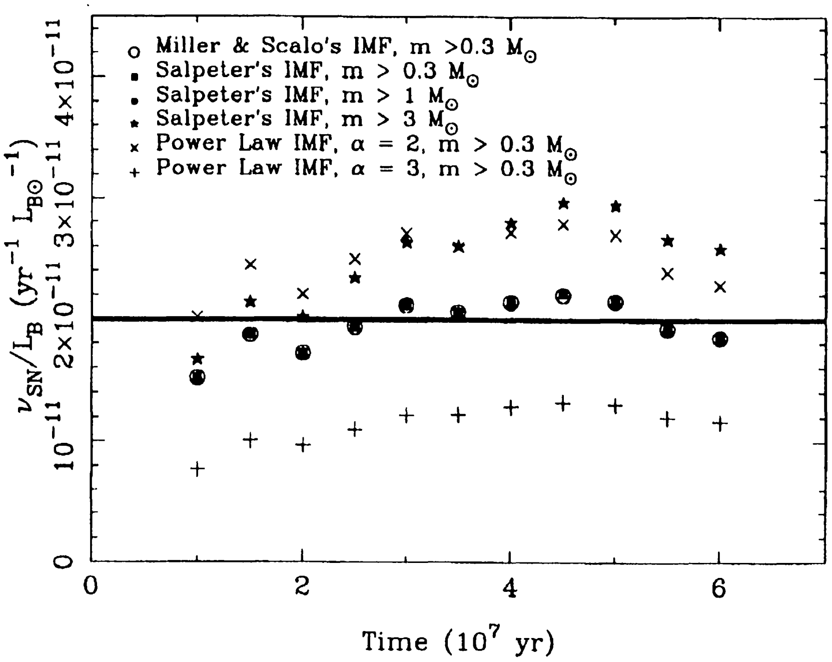

Fig. 3a. Evolution of the ratio SN rate-stellar blue luminosity of the cluster for the SN II phase of the cluster.

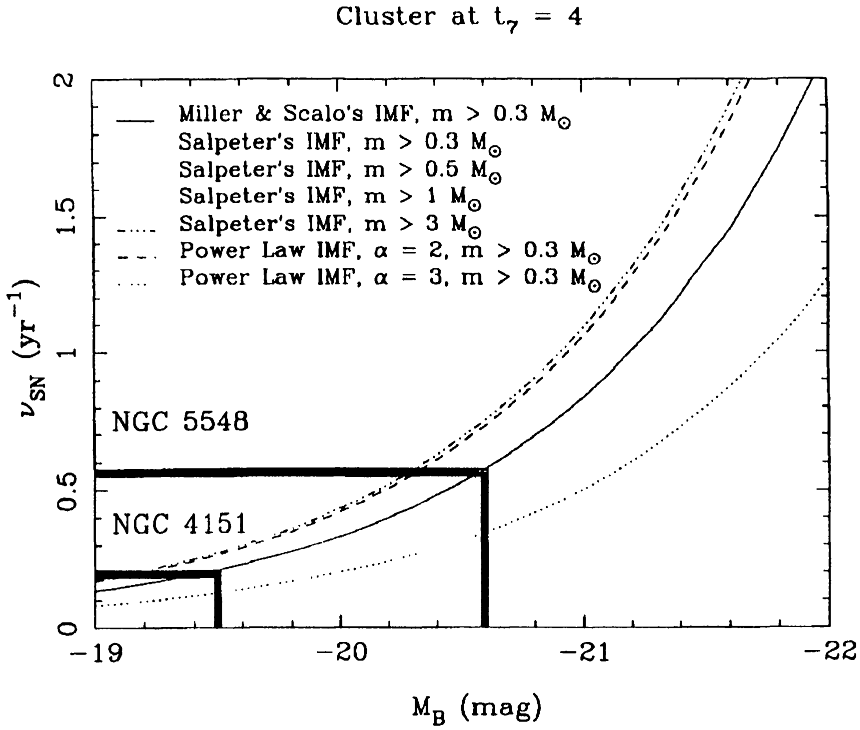

Fig. 3b. Relation SN rate-stellar blue absolute magnitude of the cluster.

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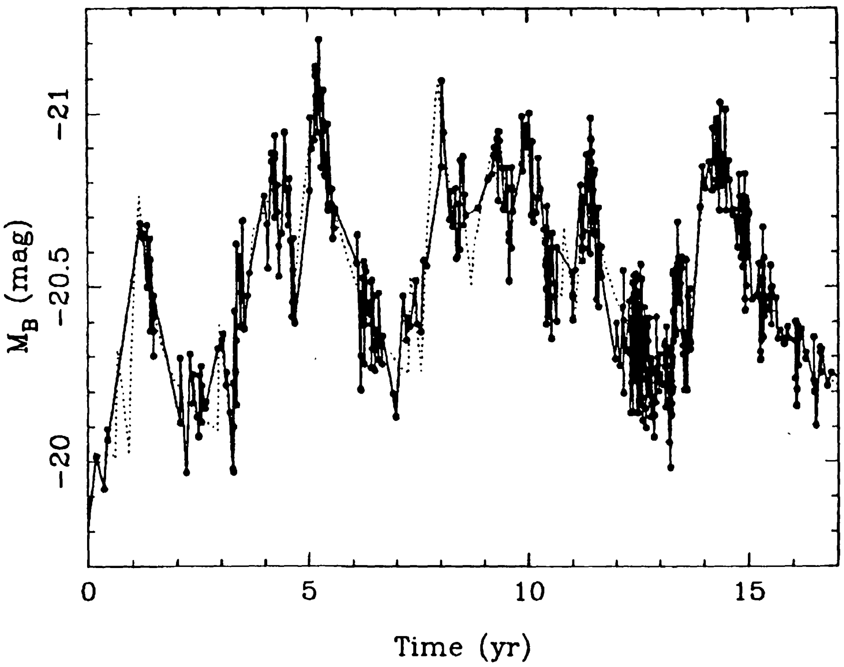

Fig. 4a. Simulated light curves for $\nu_{SN} = 0.3$ yr^{-1}, and within a factor 1.5 random $\overline{\epsilon_{51}} = 3.0$, $\overline{n_7} = 1$.

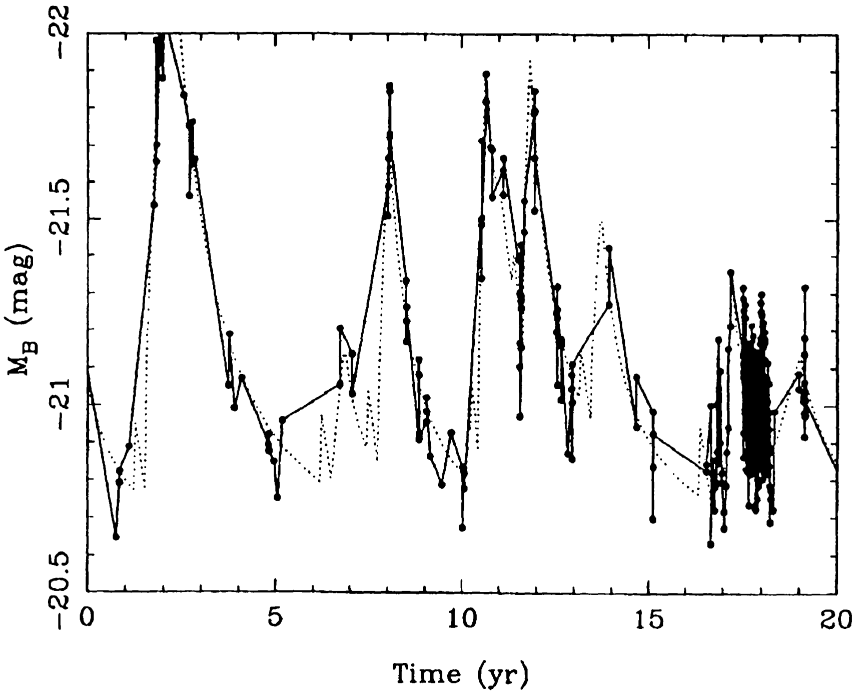

Fig. 4b. Simulated light curves for $\nu_{SN} = 0.5$ yr^{-1}, and within a factor 2 random $\overline{\epsilon_{51}} = 4.0$, $\overline{n_7} = 1$.

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phase. Fig. 3b transforms this same relation into SN rate vs. blue magnitude of the stars in the cluster for an age about 40 Myr.

Assuming that in these nuclei the luminosity at minimum arises from the stars in the young stellar cluster, the deduced SN rate is about 0.2 yr^{-1} for NGC 4151 and 0.6 yr^{-1} for NGC 5548.

The time evolution of the B luminosity of these SNe has been described in Sect. 2, where ϵ_{51} and n_7 are free parameters. However, these parameters are constrained by the observations. From the photoionization models for cSNRs of Terlevich *et al.* (1992), we find that the energy of a cSNR is univocally related to the equivalent width of recombination lines, like Hβ, outcoming from the cluster:

$$W(\mathrm{H}\beta) \sim 40\,\text{Å}\ \frac{\epsilon_{51}}{1 + 0.17\epsilon_{51}}, \tag{3}$$

which means $\overline{\epsilon_{51}} \sim 3$ for NGC 4151 (Antonucci and Cohen, 1983) and $\overline{\epsilon_{51}} \sim 4$ for NGC 5548 (Peterson, 1987; Peterson *et al.*, 1991). The circumstellar density n_7 can be derived from the amplitude of well sampled isolated peaks, like that in Fig. 2, or from variability descriptors of the whole light curve, like the r.m.s., peak-to-peak variation, etc. For both nuclei, we find $n_7 \sim 1$.

Assuming that the SN explosions are random events under the derived rates, we have simulated theoretical light curves for the cluster (dotted lines in Fig. 4). In order to make a more realistic comparison between simulated and observed light curves, we have introduced gaussian errors for a sample of points of similar intervals as those the galaxies have been observed. This simulates the inherent instrumental errors of the observations, typically $\sigma^0 \sim 0.1$ mag. The simulations are shown in Fig. 4, and should be compared to Fig. 1.

4. Conclusions

We have shown that the Starburst model provides a reasonable explanation of the optical light curves of the best sampled Seyfert 1s:

1. Observed SNe can account for the energy and amplitude variations of individual peaks in the light curves of the nuclei.
2. Numerical simulations under normal stellar evolution can reproduce the general shape of the light curves.

Furthermore, the luminosity at minimum is a good predictor of the number of observed peaks, as expected in the Starburst model.

Acknowledgements

We want to thank M.V. Penston, who kindly provided us the light curve of NGC 4151, and O. Lahav, who made available to us his code for correcting radial velocities from the Virgo Cluster influence. IA acknowledges RGO/IoA for hospitality, and the Basque Government and the Spanish DGICYT for financial support through grant BFI88.009 and project PB900182.

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